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Crises and Risks in Engineering Project Management: Identification and Classification, Crisis Triggers and Early Warning Indicators, Lessons Learned and Implications

Mohamed O. Almangoush[1*], Tarek M. Baayou[2], Midhat E. M. Esmail[3], Haytham A. Alfitees[4]
[1,3,4] General Department, College of Civil Aviation, Misrata, Libya
[2]Department of Biomedical Engineering, Faculty of Medical Technology, Misrata, Libya

الأزمات والمخاطر في إدارة المشاريع الهندسية: تحديدها وتصنيفها، ومحفزات الأزمات ومؤشرات الإنذار المبكر، والدروس المستفادة والآثار المترتبة عليها

محمد عمر المنقوش[1*]، طارق محمد بعيو[2]، مدحت اسماعيل المبروك اسماعيل[3]، هيثم عبدالله الفطيسي[4]
[1،3،4] القسم العام، كلية الطيران المدني، مصراتة، ليبيا
[2] قسم هندسة المعدات الطبية، كلية التقنية الطبية، مصراتة، ليبيا

*Corresponding author: mohamed.o.el.2015@gmail.com

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Abstract:
This article investigates crises and risks in engineering project management through an integrated and life-cycle-oriented perspective. The study first establishes a conceptual framework that clearly distinguishes risks as anticipatory, probabilistic conditions from crises as realized, high-impact events, and clarifies their interdependencies across the project life cycle. It then presents a systematic approach for the identification and classification of engineering project risks, encompassing technical, financial, organizational, environmental, and external domains, and demonstrates how unmanaged risk accumulation can escalate into project crises. The article further analyzes key crisis triggers and early warning indicators, highlighting the role of weak signals, risk escalation mechanisms, and monitoring and control systems in crisis prevention. In addition, the study evaluates proactive and reactive risk and crisis management strategies, including risk mitigation, contingency planning, resilience engineering, decision-making under uncertainty, and leadership responses during crisis situations. Drawing on empirical lessons from past engineering project failures, the article synthesizes best practices and governance implications for enhancing project robustness and sustainability. The findings emphasize that engineering project crises are rarely sudden or unforeseeable, but rather the result of cumulative risks combined with delayed recognition and weak governance. The article concludes that integrating systematic risk identification, early warning detection, adaptive management strategies, and institutional learning within a unified governance framework is essential for improving resilience and achieving sustainable engineering project outcomes.

Keywords: Engineering Project Management; Risk Management; Crisis Management; Early Warning Indicators.

الملخص:
تتعرض المشاريع الهندسية بصورة متزايدة لمخاطر معقدة ومتشابكة ناتجة عن عدم اليقين التكنولوجي، والتجزؤ التنظيمي، والقيود المالية، والضغوط التنظيمية، وتقلبات البيئات الخارجية. وعلى الرغم من التطور الملحوظ في أدوات ومنهجيات إدارة المشاريع، لا تزال العديد من المشاريع الهندسية تعاني من اضطرابات حادة وإخفاقات كبيرة، مما يشير إلى وجود

فجوة مستمرة بين ممارسات إدارة المخاطر والقدرة الفعلية على منع الأزمات. تتناول هذه الدراسة الأزمات والمخاطر في إدارة المشاريع الهندسية من منظور تكاملي قائم على دورة حياة المشروع. تقدم الدراسة أولًا إطارًا مفاهيميًا يميز بوضوح بين المخاطر بوصفها حالات احتمالية استباقية، والأزمات بوصفها أحداثًا متحققة عالية التأثير، مع توضيح علاقات الترابط بينهما عبر مراحل دورة حياة المشروع. كما تعرض منهجية منظمة لتحديد وتصنيف مخاطر المشاريع الهندسية، تشمل الجوانب التقنية والمالية والتنظيمية والبيئية والخارجية، وتبين كيف يمكن لتراكم المخاطر غير المُدارة أن يتصاعد ليؤدي إلى أزمات على مستوى المشروع. وتناقش الدراسة كذلك محفزات الأزمات ومؤشرات الإنذار المبكر، مع التأكيد على دور الإشارات الضعيفة، وآليات تصاعد المخاطر، وأنظمة المتابعة والرقابة في منع نشوء الأزمات. إضافة إلى ذلك، تُقيّم الدراسة استراتيجيات إدارة المخاطر والأزمات الاستباقية والتفاعلية، بما في ذلك تخفيف المخاطر، والتخطيط للطوارئ، وهندسة المرونة، واتخاذ القرار في ظل عدم اليقين، ودور القيادة أثناء الأزمات. واستنادًا إلى الدروس المستخلصة من إخفاقات المشاريع الهندسية السابقة، تُلخص الدراسة أفضل الممارسات والآثار الحاكمة اللازمة لتعزيز متانة المشاريع واستدامتها. وتؤكد النتائج أن أزمات المشاريع الهندسية نادرًا ما تكون مفاجئة أو غير متوقعة، بل هي غالبًا نتيجة لتراكم المخاطر مقترنًا بتأخر التعرف عليها وضعف الحوكمة. وتخلص الدراسة إلى أن دمج التحديد المنهجي للمخاطر، والكشف المبكر عن مؤشرات الإنذار، واستراتيجيات الإدارة التكيفية، والتعلم المؤسسي ضمن إطار حوكمة موحد يُعد أمرًا أساسيًا لتعزيز المرونة وتحقيق مخرجات مستدامة للمشاريع الهندسية.

الكلمات المفتاحية: إدارة المشاريع الهندسية؛ إدارة المخاطر؛ إدارة الأزمات؛ مؤشرات الإنذار المبكر.

1. Introduction

Engineering projects are inherently complex socio-technical systems characterized by high levels of uncertainty, multiple stakeholders, stringent performance constraints, and dynamic operating environments. As project scale and technological sophistication increase, so does exposure to diverse risks that can adversely affect cost, schedule, quality, safety, and sustainability [1,2]. While risks are an intrinsic aspect of engineering projects and can often be anticipated and managed, failures in recognizing, assessing, or governing these risks frequently lead to severe disruptions. Consequently, crises in engineering project management have become a recurring concern, revealing limitations in traditional planning- and control-oriented management approaches [3].

A critical challenge in this context lies in the identification and classification of risks and in clearly distinguishing risks from crises. Risks represent potential, probabilistic conditions that may affect project objectives, whereas crises are realized, high-impact events that threaten project viability. In practice, however, these concepts are often conflated, obscuring the mechanisms through which risks accumulate, interact, and escalate across the project life cycle [4,5]. Moreover, engineering project crises are rarely sudden; they are typically preceded by identifiable crisis triggers and early warning indicators, such as performance deviations, governance delays, safety near-misses, and stakeholder conflicts. The failure to detect, escalate, or respond to these signals in a timely manner remains a major contributor to project breakdowns [6-9].

Against this background, this article investigates crises and risks in engineering project management through an integrated perspective that encompasses risk identification and classification, crisis triggers and early warning indicators, and lessons learned from past project failures. By synthesizing conceptual frameworks and empirical insights, the study highlights the importance of proactive risk governance, robust monitoring and control systems, and organizational learning in preventing crisis escalation. The discussion further outlines key implications for engineering project management practice, emphasizing the need for resilience-oriented strategies and governance reforms to enhance project robustness and long-term sustainability.

Several studies [10,11] have outlined how risks in large-scale engineering projects escalate into crises due to complexity and interdependencies. These studies report that cost overruns, schedule delays, and technical failures often stem from the accumulation of multiple moderate risks rather than from a single catastrophic event. The findings emphasize that fragmented risk management practices and weak coordination between project stakeholders significantly increase the likelihood of crisis emergence.

Prior researches [12-14] have focused on identifying early warning indicators as predictors of project distress and failure. These studies highlight performance-based signals such as declining schedule and cost indices, increased rework rates, safety near-misses, and stakeholder dissatisfaction as critical precursors to crises. The literature consistently shows that while such indicators are detectable early, they are frequently ignored due to optimism bias, organizational inertia, or governance deficiencies.

A stream of studies has analyzed the role of governance and decision-making structures in engineering project crises. The results indicate that unclear authority, delayed approvals, and weak escalation mechanisms exacerbate risk escalation and hinder timely intervention. Strong governance frameworks, clear accountability, and empowered leadership are identified as key factors in reducing crisis severity and improving recovery outcomes.

Previous studies [15-17] on post-project evaluations and failure analyses emphasize the importance of learning and resilience in engineering project management. These studies find that organizations often fail to institutionalize lessons learned, leading to repeated mistakes across projects. Integrating resilience engineering principles, continuous learning mechanisms, and sustainability considerations into project management practices is shown to enhance long-term project robustness and reduce vulnerability to future crises.

This study contributes to engineering project management by clarifying the conceptual distinction between risks as probabilistic, anticipatory conditions and crises as realized, high-impact disruptions, while explaining their interdependencies across the project life cycle. It proposes an integrated framework for the systematic identification and classification of engineering project risks across technical, financial, organizational, environmental, and external domains, emphasizing how risk accumulation and interaction can escalate into crises. The study further advances crisis prevention by explicitly linking crisis triggers and early warning indicators to escalation mechanisms, thereby demonstrating how weak signals become critical failures when monitoring, escalation, and governance are inadequate. In addition, it synthesizes proactive and reactive management strategies, including mitigation, contingency planning, resilience engineering, decision-making under uncertainty, and crisis leadership, bridging risk management and crisis response within a unified governance perspective. Finally, it translates lessons learned from project failures into actionable implications for governance improvement, organizational learning, and sustainability-oriented practice to enhance project robustness and long-term performance.

2. Conceptual Framework of Crises and Risks in Engineering Projects

Engineering projects are inherently complex undertakings characterized by technical uncertainty, multi-stakeholder involvement, dynamic environments, and stringent constraints related to cost, time, quality, safety, and sustainability. Within this context, risk and crisis represent two closely related but conceptually distinct phenomena that significantly influence project performance and outcomes. While risks are generally understood as uncertain events that may affect project objectives, crises denote severe and disruptive situations that threaten the continuity or survival of the project itself. Failure to clearly distinguish between these concepts can lead to inadequate planning, delayed responses, and ineffective decision-making [18,19].

In engineering project management, risks emerge throughout the project life cycle and can often be anticipated, assessed, and mitigated using structured analytical tools. Crises, by contrast, typically arise when risks accumulate, interact, or are poorly managed, resulting in systemic failures or abrupt disruptions that demand immediate and often improvised responses. Understanding the transition from manageable risk to full-scale crisis is therefore essential for enhancing project resilience and governance. Table 1 presents a conceptual framework that systematically differentiates project risks and project crises across key dimensions, including definitions, characteristics, sources, predictability, management approaches, and life-cycle relevance. This framework provides a theoretical foundation for analyzing how risks evolve into crises and offers practical insights for integrating proactive risk management with effective crisis preparedness in engineering projects.

Table 1. Conceptual Framework of Crises and Risks in Engineering Projects [20-23].

Dimension	Project Risks	Project Crises
Definition	Potential uncertain events or conditions that may positively or negatively affect project objectives if they occur.	Severe, disruptive events that threaten the viability, safety, or continuation of the engineering project and require immediate response.
Nature	Probabilistic and anticipatory; identifiable and manageable in advance.	Emergent and acute; often sudden or resulting from accumulated risks.
Predictability	Predictable to varying degrees using analysis and historical data.	Largely unpredictable in timing and magnitude.
Primary Sources	Technical uncertainty, cost overruns, schedule delays, regulatory changes, stakeholder issues.	Escalation of unmanaged risks, systemic failures, cascading faults, external shocks.
Time Horizon	Short-term or long-term across the project life cycle.	Short-term with immediate and severe impact.

Impact Level	Ranges from low to high; usually manageable.	Extremely high; may cause project suspension or failure.
Management Approach	Risk identification, assessment, mitigation, and monitoring.	Crisis response, emergency decision-making, communication, and recovery planning.
Decision-Making Context	Structured and analytical.	Time-pressured and unstructured.
Interdependency	Risks may accumulate and amplify if uncontrolled.	Crises represent the manifestation of compounded risks.
Project Life Cycle Relevance	Dominant during planning and execution; relevant throughout.	Critical during execution and commissioning phases.

Table 1 illustrates the fundamental distinctions and interdependencies between risks and crises in engineering project management. From a definitional perspective, risks are framed as potential uncertain events, whereas crises are portrayed as realized, high-impact disruptions. This distinction underscores the temporal relationship between the two concepts, where risks precede crises and, if unmanaged, may escalate into them. In terms of nature and predictability, risks are characterized by their probabilistic and anticipatory attributes, allowing them to be analyzed through forecasting, modeling, and historical data. Crises, however, are emergent and acute, often manifesting unexpectedly or following a prolonged period of warning signals that were overlooked or underestimated. This contrast highlights the importance of early detection mechanisms and continuous monitoring systems in engineering projects.

The sources of risks and crises further emphasize their interconnectedness. Risks commonly originate from technical complexity, design uncertainty, financial constraints, regulatory changes, and stakeholder dynamics. Crises, in turn, often arise from the escalation and interaction of these same risk sources, compounded by systemic weaknesses, governance failures, or external shocks. This progression demonstrates that crises rarely occur in isolation but are typically the outcome of cumulative risk exposure. Regarding impact and time horizon, risks may exert varying levels of influence, many of which can be absorbed through mitigation strategies. Crises, by contrast, are short-term yet extremely high-impact events that can result in project suspension, significant financial loss, reputational damage, or safety incidents. This distinction reinforces the need for differentiated management approaches.

The management strategies outlined in Table 1 reflect this divergence. Risk management relies on structured, analytical processes such as identification, assessment, mitigation, and monitoring. Crisis management, however, is inherently reactive, requiring rapid decision-making, strong leadership, effective communication, and recovery planning under conditions of severe uncertainty and time pressure. Finally, the project life-cycle relevance dimension demonstrates that while risks are present throughout all project phases, crises most frequently emerge during execution and commissioning stages, where system integration, operational stress, and stakeholder pressure are at their peak. Importantly, the table emphasizes that many crises can be traced back to deficiencies in early planning and design, underscoring the strategic value of proactive risk governance [23-26].

3. Identification and Classification of Engineering Project Risks

Engineering projects operate in environments characterized by high levels of uncertainty, technological complexity, and dynamic stakeholder interactions. As project scale and system interdependencies increase, the exposure to diverse and interconnected risks becomes inevitable. Effective project risk management therefore begins with a systematic identification and classification of risks, which forms the foundation for informed decision-making, proactive mitigation, and crisis prevention [27,28].

Risk identification in engineering projects extends beyond the recognition of isolated technical uncertainties; it encompasses financial, organizational, environmental, regulatory, social, and external macro-level factors that may adversely affect project objectives. Without a structured framework, risks are often addressed in a fragmented manner, increasing the likelihood of risk accumulation, interaction, and escalation into full-scale project crises [29,30]. Consequently, a comprehensive and integrated classification scheme is essential to capture the multi-dimensional nature of engineering project risks across the entire project life cycle.

The systematic framework presented in Table 2 (identification and classification of engineering project risks) organizes risks into coherent categories, links them to typical sources and observable warning signals, and associates them with appropriate identification techniques and performance indicators. By explicitly connecting risk categories with potential crisis escalation pathways, the framework provides both analytical clarity and practical relevance for strengthening project resilience and governance.

Table 2. Identification and Classification of Engineering Project Risks [31-34].

Risk Category	Typical Risk Sources	Common Risk Events	Early Warning Indicators	Identification Methods	Key Indicators (KPIs)	Potential Escalation to Crisis
Technical / Engineering	Design complexity, immature technology, interface issues	Design errors, rework, system failures	Repeated RFIs, test failures	Design reviews, FMEA, HAZOP	Rework %, defect rate	System failure, safety incidents
Schedule / Delivery	Unrealistic planning, dependency delays	Missed milestones, late deliveries	SPI decline, float erosion	CPM, schedule risk analysis	SPI, milestone hit rate	Contract penalties, project delay crisis
Financial / Cost	Inflation, scope creep, underestimation	Cost overruns, cash-flow gaps	Rising EAC, contingency depletion	EVM, cost risk workshops	CPI, cost variance	Funding shortfall, project suspension
Organizational / Governance	Weak decision structures, unclear roles	Slow approvals, scope drift	Decision delays, audit findings	Governance audits, RACI analysis	Approval cycle time	Loss of control, systemic failure
HSE / Safety	High-risk activities, poor safety culture	Accidents, environmental releases	Near-miss trends, unsafe acts	HIRA, safety audits	LTIFR, near-miss rate	Shutdown, legal and reputational crisis
Stakeholder / Social	Community opposition, land access	Protests, access blockages	Complaints, negative media	Stakeholder analysis, engagement plans	Grievance closure time	Loss of social license
External / Macro	Political instability, extreme weather	Force majeure, supply disruption	Security alerts, market volatility	PESTLE, scenario planning	Downtime due to incidents	Project shutdown or termination

The table 2 presents a multidimensional structure for understanding engineering project risks by aligning risk categories, sources, early indicators, identification methods, and crisis escalation mechanisms. This integrated perspective enables project managers to move from reactive risk handling to proactive and preventive risk governance.

- Technical and Engineering Risks

Technical risks originate from design complexity, immature technologies, and system integration challenges. The table highlights how recurring design changes, excessive requests for information (RFIs), and repeated test failures serve as early warning indicators. Tools such as design reviews, Failure Mode and Effects Analysis (FMEA), and hazard studies play a critical role in detecting these risks. If left unresolved, technical risks may escalate into commissioning failures or safety incidents, transforming manageable uncertainties into critical project crises.

- Schedule and Delivery Risks

Schedule-related risks are closely linked to unrealistic planning assumptions, dependency mismanagement, and procurement delays. Indicators such as declining Schedule Performance Index (SPI) and critical path erosion provide quantitative evidence of emerging threats. The table emphasizes the use of Critical Path Method (CPM) and schedule risk analysis to identify vulnerabilities. Escalation occurs when delays cascade across project interfaces, leading to contractual penalties, stakeholder dissatisfaction, and potential project termination.

- Financial and Cost Risks

Financial risks stem from cost underestimation, inflationary pressures, scope creep, and cash-flow instability. Early signs include rising estimates at completion (EAC) and rapid depletion of contingencies. Earned Value Management (EVM) and cost-risk workshops are key identification mechanisms. When financial risks are inadequately controlled, they can culminate in funding shortfalls, insolvency, or complete project suspension, representing one of the most severe forms of project crisis.

- Organizational and Governance Risks

Organizational risks arise from unclear roles, weak governance structures, and ineffective decision-making processes. Prolonged approval cycles and audit findings signal deficiencies in project control systems. Governance audits and RACI analyses are essential for identifying such risks. Escalation typically results in systemic loss of control, where misalignment among stakeholders prevents timely corrective action during critical project phases.

- Health, Safety, and Environmental (HSE) Risks

HSE risks carry particularly high consequences in engineering projects. Near-miss trends and unsafe work observations serve as leading indicators of deeper safety issues. The framework underscores the role of hazard identification and risk assessment (HIRA) and safety audits in early detection. Failure to manage HSE risks can trigger accidents, regulatory shutdowns, legal action, and severe reputational damage, constituting an immediate crisis scenario.

- Stakeholder and Social Risks

Stakeholder-related risks originate from community opposition, land access issues, and ineffective communication strategies. Rising grievance cases and negative media attention are critical early signals. Stakeholder mapping and engagement planning are essential identification tools. If ignored, these risks may escalate into social unrest, work stoppages, and loss of social license to operate, significantly disrupting project execution.

- External and Macro-Level Risks

External risks, including political instability, security threats, extreme weather events, and market volatility, are largely outside direct project control. Scenario planning and PESTLE analysis help anticipate such uncertainties. Escalation pathways include force majeure events, evacuation, supply chain collapse, or contractual renegotiation, often resulting in project shutdown or long-term suspension.

Overall, the table 2 demonstrates that engineering project risks are interconnected, dynamic, and cumulative. Risks rarely escalate into crises due to a single failure; rather, crises emerge from the interaction of multiple risk categories combined with delayed recognition or ineffective governance. By linking early warning indicators with appropriate identification methods and crisis escalation pathways, the framework provides a practical tool for strengthening anticipatory capacity and resilience in engineering project management.

4. Crisis Triggers and Early Warning Indicators in Engineering Projects

Engineering projects are increasingly exposed to complex and interconnected sources of uncertainty arising from technological innovation, organizational fragmentation, financial constraints, regulatory pressures, and volatile external environments. While traditional risk management practices focus on identifying and mitigating isolated uncertainties, many project failures are not the result of single risk events but rather the culmination of escalating risks that evolve into full-scale crises. Understanding the mechanisms through which risks transform into crises is therefore essential for improving project resilience and preventing catastrophic outcomes [35,36]. Figure 1 shows crisis triggers and early warning.

Figure 1. Crisis Triggers and Early Warning Indicators in Engineering Projects.

Crises in engineering projects are rarely sudden or unpredictable. In most cases, they are preceded by early warning indicators such as declining performance metrics, repeated technical anomalies, governance delays, safety near-misses, or stakeholder tensions. These weak signals, if detected and acted upon in a timely manner, provide valuable opportunities for intervention before irreversible damage occurs. However, ineffective monitoring systems, poor information integration, and delayed decision-making often allow these signals to be normalized or ignored [37,38].

This section examines the key crisis trigger categories and their associated early warning indicators in engineering projects. By analyzing technical, financial, organizational, human, safety, supply chain, stakeholder, regulatory, and external drivers, the discussion highlights how risk escalation mechanisms operate across the project life cycle. Emphasis is placed on the role of monitoring and control systems in translating early signals into preventive action, thereby reducing the likelihood of crisis emergence [39-41].

A. Technical System Failure

Technical system failure represents one of the most critical crisis triggers in engineering projects. It is commonly driven by design flaws, interface incompatibilities, inadequate testing, and the deployment of immature technologies. Early warning indicators include repeated test failures, persistent design changes, unresolved technical queries, and abnormal system performance during trials. When such indicators are ignored, localized technical risks can propagate across interconnected subsystems, leading to systemic failure during construction, commissioning, or operation. Effective monitoring through design reviews, failure analysis tools, and staged testing is essential to prevent technical risks from escalating into project-wide crises.

B. Schedule Collapse

Schedule collapse occurs when unrealistic planning assumptions, complex interdependencies, and procurement delays converge. Early warning signs are often reflected in declining schedule performance indices, erosion of float, and repeated milestone slippages. These signals indicate diminishing recovery capacity within the project schedule. If corrective action is delayed, schedule risks may cascade across work packages, compress decision windows, and trigger contractual penalties. Continuous schedule monitoring, critical path analysis, and timely re-sequencing are therefore vital to prevent schedule-related crises.

C. Cost and Cash-Flow Breakdown

Cost and cash-flow breakdowns are among the most visible and damaging crisis triggers in engineering projects. They are driven by cost underestimation, inflation, uncontrolled scope growth, and delayed payments. Early warning indicators include rising estimates at completion, declining cost performance indices, and rapid consumption of contingency reserves. Once financial stress limits execution capability or contractor solvency, the project may enter a downward spiral leading to suspension or termination. Robust financial monitoring systems and disciplined cost governance are essential to arrest escalation at an early stage.

D. Governance and Decision Failure

Governance and decision failure arise from unclear authority, weak leadership, fragmented reporting, and slow approval processes. Early warning indicators include prolonged decision latency, inconsistent directives, and recurring audit findings. These issues inhibit timely intervention and amplify existing risks across technical, schedule, and financial domains. Without effective escalation mechanisms, governance failures can rapidly evolve into systemic crises. Strong project governance structures, clear decision rights, and empowered leadership are critical for maintaining control under uncertainty.

E. Human Resource Degradation

Human resource degradation is a less visible but equally significant crisis trigger. Skills shortages, high staff turnover, fatigue, and inadequate supervision often manifest through declining productivity, increased error rates, and rising safety incidents. These indicators suggest a gradual erosion of execution capacity. When left unaddressed, workforce instability undermines quality, safety, and schedule performance, increasing the likelihood of broader project crises. Continuous workforce monitoring, competency management, and fatigue control systems play a key preventive role.

F. Health, Safety, and Environmental (HSE) Breakdown

HSE breakdowns represent high-impact crisis triggers with immediate consequences. Unsafe practices, weak safety culture, and poor environmental controls are typically preceded by increased near-miss reporting, repeated violations, and environmental exceedances. These early signals indicate latent conditions that may culminate in serious accidents or regulatory shutdowns. Given the rapid escalation potential, real-time HSE monitoring and strict enforcement of control measures are essential components of crisis prevention in engineering projects.

G. Supply Chain Disruption

Supply chain disruption emerges from single-source dependencies, supplier instability, and logistics constraints. Early warning indicators include late deliveries, repeated quality nonconformities, and increased expediting activity. As material shortages halt critical construction activities, supply chain risks can quickly trigger schedule and cost crises. Proactive supplier monitoring, diversification strategies, and contingency planning are therefore necessary to enhance supply chain resilience.

H. Stakeholder and Social Conflict

Stakeholder and social conflict are an increasingly prominent crisis trigger in large engineering projects. Poor communication, community opposition, and land access disputes often surface through escalating complaints, protests, and negative media coverage. These signals reflect a deteriorating social license to operate. If ignored, stakeholder risks can lead to access denial, work stoppages, and reputational damage. Systematic stakeholder engagement and grievance management systems are essential for early detection and mitigation.

I. Regulatory and Compliance Shock

Regulatory and compliance shocks arise from evolving legal frameworks, permit delays, and non-compliance with standards. Early warning indicators include failed inspections, repeated permit re-submissions, and regulatory warnings. When compliance risks escalate, authorities may impose stop-work orders or require costly redesigns, significantly disrupting project execution. Continuous regulatory monitoring and proactive engagement with authorities are critical to preventing compliance-related crises.

J. External Shock Events

External shock events, such as political instability, security threats, extreme weather, and pandemics, are largely beyond project control yet have profound crisis potential. Early warning signals may include security alerts, weather forecasts, or market volatility. These events can rapidly overwhelm existing project controls and force emergency responses. Scenario planning, business continuity plans, and adaptive contractual mechanisms are essential for mitigating the impact of external shocks.

The analysis of crisis triggers and early warning indicators demonstrates that engineering project crises are predominantly the outcome of progressive and cumulative risk escalation, rather than abrupt or unforeseeable events. Across all categories, technical, schedule, financial, governance, human resources, health and safety, supply chain, stakeholder, regulatory, and external, distinct warning signals consistently emerge well before crisis materialization. These indicators provide a critical window for corrective intervention, provided that projects possess the necessary monitoring capability and decision authority.

The findings underscore that effective crisis prevention depends not only on the availability of analytical tools and performance metrics, but also on organizational readiness to recognize weak signals and act decisively. Weak governance structures, delayed escalation, and fragmented information flows remain central contributors to crisis amplification. Conversely, integrated monitoring systems, clear decision rights, and proactive leadership significantly enhance the ability to interrupt escalation pathways. In conclusion, embedding early warning systems within a robust project governance framework is essential for transforming risk management from a reactive function into a strategic capability. By systematically identifying crisis triggers and responding to early indicators, engineering projects can enhance resilience, protect stakeholder value, and achieve sustainable performance even in highly uncertain environments.

5. Risk and Crisis Management Strategies in Engineering Projects

Engineering projects operate within environments marked by high uncertainty, technological complexity, and dynamic stakeholder expectations. As project systems become increasingly interconnected, the consequences of unmanaged risks can propagate rapidly, transforming localized disruptions into full-scale crises [42,43]. Traditional risk management approaches, which often emphasize compliance and static risk registers, are no longer sufficient to address the speed, scale, and systemic nature of contemporary engineering challenges. This necessitates a comprehensive integration of risk management and crisis management strategies within a unified project governance framework as outlined in Figure 2.

Risk and crisis management strategies in engineering projects encompass both proactive measures, aimed at preventing adverse events, and reactive responses, designed to contain and recover from disruptions when they occur. Proactive strategies include early risk identification, mitigation planning, contingency allocation, and resilience-oriented system design. Reactive strategies focus on crisis response, rapid decision-making under uncertainty, leadership coordination, and effective communication during high-pressure situations [44,45].

This section evaluates key risk and crisis management strategies applicable to engineering projects, emphasizing mitigation, contingency planning, resilience engineering, decision-making under uncertainty, leadership response, and organizational learning. By examining these strategies in an integrated manner, the discussion highlights how engineering projects can reduce vulnerability, enhance adaptive capacity, and improve performance in the face of both foreseeable risks and unforeseen crises [46-50].

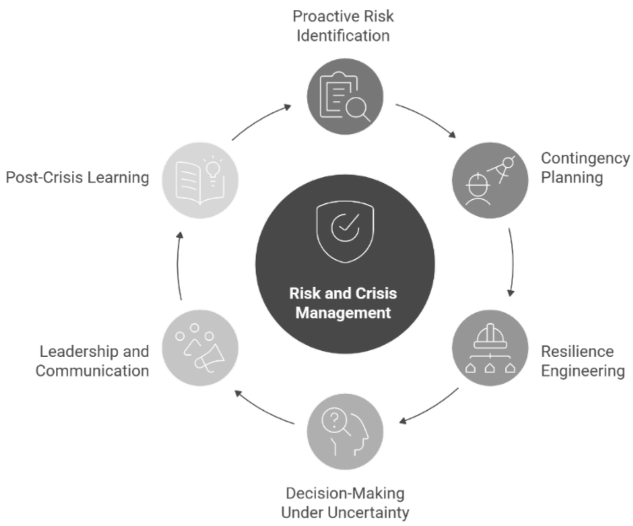

Figure 2. Risk and Crisis Management Strategies in Engineering Projects.

A. Proactive Risk Identification and Mitigation Strategies

Proactive risk management focuses on anticipating potential threats before they materialize into disruptive events. In engineering projects, this involves systematic risk identification, qualitative and quantitative risk assessment, and the implementation of targeted mitigation measures during early project phases. Techniques such as design optimization, redundancy planning, risk-based scheduling, and financial hedging reduce both the likelihood and impact of adverse events. By addressing risks at their source, proactive mitigation minimizes the accumulation of latent vulnerabilities that could otherwise escalate into project crises.

B. Contingency Planning and Preparedness Mechanisms

Contingency planning provides structured response options for high-impact risks that cannot be fully eliminated. Engineering projects rely on predefined contingency budgets, alternative execution strategies, and emergency response plans to maintain continuity under adverse conditions. Effective contingency planning requires clear activation thresholds, ownership, and integration with project governance systems. When properly designed, contingencies enhance project flexibility and enable rapid adaptation, preventing temporary disruptions from evolving into systemic crises.

C. Resilience Engineering and Adaptive Project Design

Resilience engineering emphasizes the capacity of engineering projects to absorb disturbances, adapt to changing conditions, and recover from disruptions. This agenda highlights strategies such as modular system design, interface decoupling, redundancy, and adaptive control mechanisms. Unlike traditional risk mitigation, resilience-oriented approaches accept uncertainty as inherent and focus on sustaining functionality under stress. Incorporating resilience principles strengthens project robustness and reduces sensitivity to cascading failures during crisis situations.

D. Decision-Making Under Uncertainty and Time Pressure

Crisis situations demand rapid decision-making in the presence of incomplete information and heightened uncertainty. Engineering project managers must balance analytical rigor with intuitive judgment, often relying on scenario analysis, expert elicitation, and real-time data. This agenda examines structured decision-support tools, escalation protocols, and authority delegation mechanisms that enable timely and coherent responses. Effective decision-making under uncertainty is critical to limiting crisis duration and preventing secondary impacts.

E. Leadership and Communication During Project Crises

Leadership plays a decisive role in shaping project outcomes during crises. Strong crisis leadership is characterized by clear direction, transparent communication, and the ability to maintain stakeholder confidence under pressure. This agenda explores leadership behaviors that promote coordination, trust, and accountability during disruptive events. Consistent and credible communication, both internal and external, reduces misinformation, aligns stakeholder expectations, and supports collective problem-solving throughout crisis response and recovery phases.

F. Post-Crisis Learning and Organizational Improvement

Post-crisis learning transforms adverse experiences into long-term organizational value. Engineering projects that systematically capture lessons learned, conduct root cause analysis, and update risk management practices enhance their future resilience. This agenda emphasizes the importance of institutional learning mechanisms, knowledge repositories, and feedback loops that integrate crisis insights into standards, procedures, and training. By embedding learning into project governance, organizations reduce the likelihood of recurring failures and strengthen continuous improvement.

The analysis of risk and crisis management strategies demonstrates that successful engineering project outcomes depend on the integration of preventive, responsive, and adaptive capabilities. Proactive risk mitigation and contingency planning reduce exposure to known threats, while resilience-based design and adaptive execution enable projects to withstand and recover from unexpected disruptions. However, when crises do occur, the effectiveness of response is largely determined by the quality of leadership, clarity of decision-making structures, and robustness of communication mechanisms. A key insight is that risk and crisis management should not be treated as separate or sequential functions. Instead, they form a continuous management cycle in which early risk identification, preparedness, real-time response, and post-crisis learning are closely interconnected. Projects that lack this integration are more likely to experience delayed responses, cascading failures, and prolonged recovery periods.

6. Lessons Learned and Implications for Engineering Project Management Practice

Engineering project failures and crises continue to occur despite significant advances in project management methodologies, analytical tools, and digital technologies. These failures highlight that technical competence alone is insufficient to ensure successful project outcomes in complex and uncertain environments. Instead, recurring patterns of governance weakness, inadequate risk integration, delayed decision-making, and insufficient organizational learning frequently underpin major project breakdowns. Figure 3 illustrates lessons learned and implications for engineering project management practice. Analyzing lessons learned from past engineering project crises provides valuable empirical insights into how risks escalate and why early warning signals are often ignored. Such analysis enables project managers and policymakers to move beyond reactive responses and toward evidence-based improvements in professional practice.

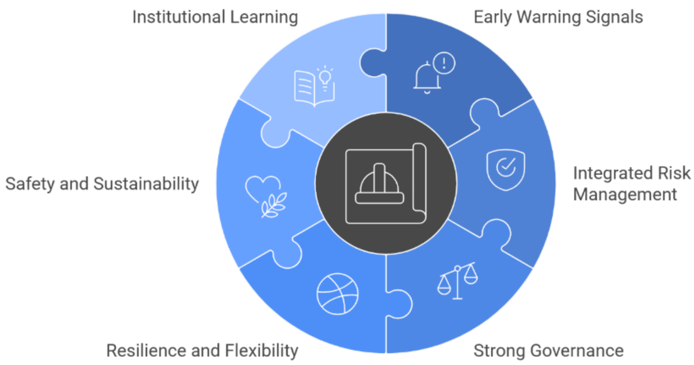

Figure 3. Lessons Learned and Implications for Engineering Project Management Practice.

A. Early Warning Signals Must Be Systematically Recognized and Escalated

A primary lesson from engineering project failures is that warning signals often emerge early but are overlooked or normalized. Effective project management practice must institutionalize mechanisms for detecting, escalating, and responding to weak signals across technical, financial, safety, and stakeholder domains.

B. Integrated Risk Management Is Essential to Prevent Risk Accumulation

Project crises typically result from the interaction of multiple moderate risks rather than a single catastrophic event. Engineering project management should adopt integrated, system-level risk assessment approaches that capture interdependencies and cascading effects instead of relying on silo-based risk registers.

C. Strong Governance and Clear Decision Authority Reduce Crisis Escalation

Deficiencies in governance structures, such as unclear accountability, delayed approvals, and fragmented authority, significantly contribute to crisis escalation. Clear decision rights, effective escalation protocols, and empowered leadership are critical for timely and coordinated responses.

D. Resilience and Flexibility Should Complement Deterministic Planning

Overreliance on rigid schedules and fixed budgets undermines a project's ability to absorb uncertainty. Engineering projects should embed resilience principles, including contingency flexibility, adaptive execution strategies, and scenario planning, to maintain performance under disruption.

E. Safety and Sustainability Must Be Embedded as Strategic Priorities

Treating health, safety, and environmental considerations as compliance obligations rather than core values increases vulnerability to major incidents. Sustainable engineering project management requires integrating safety culture, environmental stewardship, and social responsibility into strategic decision-making.

F. Institutional Learning Is Critical for Long-Term Improvement

Recurrent failures often reflect inadequate learning from past projects and crises. Engineering organizations must formalize lesson-capture processes, knowledge management systems, and continuous improvement practices to prevent the repetition of known mistakes and enhance long-term project robustness.

The lessons learned from engineering project failures and crises demonstrate that effective project management is fundamentally a systemic and governance-driven challenge, rather than a purely technical one. Crises typically emerge from the accumulation and interaction of multiple risks combined with weak escalation mechanisms and delayed leadership responses. Recognizing early warning indicators, integrating risks across domains, and empowering timely decision-making are therefore critical to preventing crisis escalation. Furthermore, embedding resilience, safety, and sustainability into core project strategies enhances the capacity of engineering projects to withstand uncertainty and recover from disruption. Equally important is the institutionalization of learning mechanisms that ensure insights from past failures are systematically captured and applied to future projects.

7. Conclusion

This article has provided an integrated and systematic examination of crises and risks in engineering project management, synthesizing conceptual foundations, empirical insights, and practical implications across the project life cycle. By clearly distinguishing between risks as anticipatory, probabilistic conditions and crises as realized, high-impact disruptions, the study establishes a coherent conceptual framework that clarifies their interdependencies and escalation pathways. This distinction is essential for overcoming the limitations of traditional project management approaches that often conflate risk management with crisis response. Through a structured identification and classification of engineering project risks, the article demonstrates that project crises rarely originate from isolated events. Instead, they emerge from the cumulative interaction of technical, financial, organizational, environmental, and external risks that are insufficiently recognized, monitored, or governed. The analysis underscores the inadequacy of fragmented, silo-based risk registers and highlights the need for integrated, system-level risk assessment capable of capturing interdependencies and cascading effects.

The discussion of crisis triggers, and early warning indicators further reveals that engineering project crises are typically preceded by observable weak signals, including performance deviations, governance delays, safety near-misses, and stakeholder tensions. The failure to detect, escalate, or act upon these indicators remains a primary contributor to crisis escalation. Accordingly, the study emphasizes the critical role of robust monitoring and control systems, supported by clear escalation protocols and decision authority, in preventing risks from transforming into crises. In evaluating risk and crisis management strategies, the article highlights the importance of combining proactive measures, such as risk mitigation, contingency planning, and resilience-oriented design, with effective reactive responses during crisis situations. Decision-making under uncertainty, strong leadership, and transparent communication are shown to be decisive factors in limiting crisis impacts and enabling recovery. The findings suggest that resilience engineering and adaptive governance are increasingly indispensable in managing the complexity and uncertainty inherent in modern engineering projects.

Finally, the synthesis of lessons learned and implications for practice demonstrates that repeated project failures are often rooted in governance weaknesses, overreliance on deterministic planning, and insufficient organizational learning. Embedding safety, sustainability, and resilience as strategic priorities, rather than treating them as compliance obligations, emerges as a critical requirement for long-term project success. Institutionalizing learning mechanisms and aligning policy frameworks with robust risk governance further strengthen project robustness and sustainability. In conclusion, this article argues that effective management of crises and risks in engineering projects requires an integrated, life-cycle-oriented approach that unifies conceptual clarity, systematic risk identification, early warning detection, adaptive management strategies, and continuous learning. By adopting such an approach, engineering project organizations can enhance resilience, safeguard stakeholder value, and improve the likelihood of delivering complex projects successfully in increasingly uncertain and dynamic environments.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, M.A., T.B., M.E. and H.A.; methodology, M.A., T.B., M.E. and H.A.; validation, M.A., T.B., M.E. and H.A.;; investigation, M.A., T.B., M.E. and H.A.; resources, M.A. and T.B.,; data curation, M.E. and H.A.; writing, original draft preparation, M.A., T.B., M.E. and H.A.; writing, review and editing, M.A., T.B., M.E. and H.A.; visualization, M.A., T.B., M.E. and H.A.; project administration, M.A.

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References:

[1] G. Castelblanco, E. M. Fenoaltea, A. De Marco, and B. Chiaia, "Influence of macroeconomic factors on construction costs: an analysis of project cases," *Constr. Manage. Econ.*, pp. 1–17, 2024.

[2] X. Ren, S. Xu, J. Yu, and F. Lin, "The impact of project managers' psychological resilience on adaptive performance: A multilevel model," *Proj. Manage. J.*, vol. 56, no. 2, pp. 198–213, 2025.

[3] M. M. Firose, B. N. M. Chathurangi, and I. Kamardeen, "Work stress among construction professionals during an economic crisis: a case study of Sri Lanka," *Smart Sustain. Built Environ.*, 2025.

[4] A. Rajapaksha, B. A. K. S. Perera, and T. N. Liyanawatta, "Framework for avoidance of disputes arising in the construction industry due to the economic crisis," *J. Leg. Aff. Dispute Resolut. Eng. Constr.*, vol. 17, no. 1, 2025.

[5] K. Kim, H. R. Tiedmann, and K. M. Faust, "Construction industry changes induced by the COVID-19 pandemic," *Eng. Constr. Archit. Manage.*, vol. 32, no. 7, pp. 4413–4438, 2025.

[6] B. De Simone, G. Deeken, and F. Catena, "Balancing ethics and innovation: Can artificial intelligence safely transform emergency surgery? A narrative perspective," *J. Clin. Med.*, vol. 14, no. 9, p. 3111, 2025.

[7] M. Panda, M. M. Hossain, R. Puri, and A. Ahmad, "Artificial intelligence in action: shaping the future of public sector," *Digit. Pol. Regul. Gov.*, vol. 27, no. 6, pp. 668–686, 2025.

[8] R. Arnaudova, E. Viza, and M. Cano, "Rethinking risk management in times of crisis: the effect of COVID-19 on small and medium-sized enterprises in Scotland," *TQM J.*, vol. 37, no. 2, pp. 484–503, 2025.

[9] M. Cotton, S. Langford, A. Kuria, and K. Parkhill, "A technology to solve the water-energy-food crisis? Mapping sociotechnical configurations of agrivoltaics using Q-methodology," *Energy Res. Soc. Sci.*, vol. 119, no. 103872, p. 103872, 2025.

[10] B. Badhon, R. K. Chakrabortty, S. G. Anavatti, and M. Vanhoucke, "A multi-module explainable artificial intelligence framework for project risk management: Enhancing transparency in decision-making," *Eng. Appl. Artif. Intell.*, vol. 148, no. 110427, p. 110427, 2025.

[11] M. Orellano and D. Gourc, "What typology of risks and methods for risk management in innovation projects?: A systematic literature review," *Int. J. Innov. Stud.*, vol. 9, no. 1, pp. 1–15, 2025.

[12] J. R. Turner, "How good governance leads to better project performance through improved decision-making," *Int. J. Manag. Proj. Bus.*, vol. 18, no. 2, pp. 434–452, 2025.

[13] T. Butsch, R. Bell, and V. Warren, "Decision-making in organizational crisis in traditional and self-managed organizations: toward a hybrid approach," *Strateg. HR Rev.*, vol. 24, no. 5, pp. 206–209, 2025.

[14] Y. Hua, M. Kang, H. Yao, and Y. Fu, "How to foster Project Organization Resilience in the construction industry: The role of data governance capabilities," *Buildings*, vol. 15, no. 8, p. 1219, 2025.

[15] Y. Qian, J. Jiang, B. Guo, and F. Hu, "The impact of 'zero-waste city' pilot policy on corporate green transformation: a causal inference based on double machine learning," *Front. Environ. Sci.*, vol. 13, no. 1564418, 2025.

[16] A. Rehan, D. Thorpe, and A. Heravi, “An empirical study on project managers’ leadership behavioral practices impacting project success – the Australian construction sector,” *Int. J. Constr. Educ. Res.*, vol. 21, no. 2, pp. 164–188, 2025.

[17] H. C. O. Unegbu, D. S. Yawas, B. Dan-asabe, and A. A. Alabi, “Measures for overcoming sustainable construction barriers in the Nigerian construction industry,” *Discov Civ Eng*, vol. 2, no. 1, 2025.

[18] A. Olmedo and J. Muir, “Beyond crisis: Enhancing behavioral response through a conceptual framework,” *J. Am. Psychiatr. Nurses Assoc.*, vol. 31, no. 2, pp. 111–120, 2025.

[19] S. A. Samoilenko, “Emergent conceptual frameworks of disruption, character assassination, and visual disinformation in crisis communication research,” *Communication and Misinformation*. Wiley, pp. 63–76, 08-Jan-2025.

[20] Y. Wang, R. Gong, P. Xu, and C. Shen, “Exploring dynamic public trust in mega infrastructure projects during online public opinion crises of extreme climate emergencies: Users’ behaviors, trust dimensions, and effectiveness of strategies,” *Risk Anal.*, vol. 45, no. 5, pp. 1044–1054, 2025.

[21] K. Klasa, B. D. Trump, S. Dulin, M. Smith, H. Jarman, and I. Linkov, “A resilience-augmented approach to compound threats and risk governance: A systems perspective on navigating complex crises,” *Environments*, vol. 12, no. 2, p. 64, 2025.

[22] Z. Zungu, S. Laryea, and R. Nkado, “A critical literature review on organizational resilience: why current frameworks are insufficient for contracting firms in the construction industry,” *Int. J. Constr. Manag.*, vol. 25, no. 15, pp. 1847–1858, 2025.

[23] M. S. Irshad *et al.*, “Interdisciplinary hybrid solar-driven evaporators: Theoretical framework of fundamental mechanisms and applications,” *Small*, vol. 21, no. 7, p. e2407280, 2025.

[24] P. Janin and Q. Chapus, “Is resilience a consensual concept? An analysis of food security projects in Burkina Faso,” *Food Ethics*, vol. 10, no. 2, 2025.

[25] M. Neri, F. Niccolini, and F. Virili, “Organizational cyber resilience: toward an integrative conceptual framework,” *Manag. Rev. Q.*, 2025.

[26] P. L. M. Tolentino, R. D. Williams, and M. D. Hurst, “Natural flood risk management in tropical Southeast Asia: Prospects in the biodiverse archipelagic nation of the Philippines,” *WIREs Water*, vol. 12, no. 1, 2025.

[27] A. H. Turkyilmaz and G. Polat, “Identification and classification of risks in construction projects: clusters, trend studies and risk breakdown structure,” *Eng. Constr. Archit. Manage.*, 2025.

[28] Z. Guo *et al.*, “Enhanced risk-based quality control for hydraulic engineering construction projects considering the risk-influencing mechanism,” *J. Constr. Eng. Manag.*, vol. 151, no. 2, 2025.

[29] M. A. Isah and B.-S. Kim, “Question-answering system powered by knowledge graph and generative pretrained transformer to support risk identification in tunnel projects,” *J. Constr. Eng. Manag.*, vol. 151, no. 1, 2025.

[30] T. Dong, H. Li, and Z. Zhang, “The using effect of fuzzy analytic hierarchy process in project engineering risk management,” *Neural Comput. Appl.*, vol. 37, no. 12, pp. 7935–7945, 2025.

[31] T. Yuan, X. Zhang, and X. Chen, “Machine learning based enterprise financial audit framework and high risk identification,” *Comput. Simul. Appl.*, vol. 3, no. 1, pp. 1–10, 2025.

[32] M. H. Kazemi and A. Alvanchi, “Application of NLP-based models in automated detection of risky contract statements written in complex script system,” *Expert Syst. Appl.*, vol. 259, no. 125296, p. 125296, 2025.

[33] M. Sun, Y. Liu, L. Zhao, W. Xie, and W. Mao, “Advances and challenges in assessing submarine landslide risks to marine infrastructure,” *Nat. Hazards (Dordr.)*, vol. 121, no. 7, pp. 7811–7837, 2025.

[34] M. K. S. Al-Mhdawi, A. O’connor, A. Qazi, F. Rahimian, and N. Dacre, “Review of studies on risk factors in critical infrastructure projects from 2011 to 2023,” *Smart Sustain. Built Environ.*, vol. 14, no. 2, pp. 342–376, 2025.

[35] X. Yu, “Study of corporate management financial early warning combining BP algorithm and KLR,” *Int. J. Crit. Infrastruct.*, vol. 21, no. 1, pp. 87–103, 2025.

[36] D. Chovanec, B. Kollár, B. Halúsková, J. Kubás, M. Pawęska, and J. Ristvej, “A component-based approach to early warning systems: A theoretical model,” *Appl. Sci. (Basel)*, vol. 15, no. 6, p. 3218, 2025.

[37] X. Lun, Y. Wang, Q. Fu, Q. Liu, and T. Wang, "A machine-learning-dependent early warning system for corporate financial crises," *J. Comput. Methods Sci. Eng.*, vol. 25, no. 5, pp. 4581–4599, 2025.

[38] G. Chen, "Formation mechanism and early warning of financial crisis combined with data mining technology," *Int. J. Inf. Commun. Technol.*, vol. 26, no. 12, pp. 1–14, 2025.

[39] C.-F. Wu, M.-C. Lin, T.-W. Chao, and C.-C. Chiou, "Omnipresent AI and Big data for financial early warning: integrating financial indicators and text sentiment analysis in Chinese real estate," *Enterp. Inf. Syst.*, vol. 19, no. 3–4, 2025.

[40] S. N. Chattopadhyay and A. K. Gupta, "Unveiling critical transition in a transport network model: stochasticity and early warning signals," *Nonlinear Dyn.*, 2025.

[41] H. Sun, Y. Jiang, and X. Tang, "Artificial intelligence-driven academic performance early warning system for engineering universities: Application of XGBoost-SHAP algorithm," *Int. J. High Speed Electron. Syst.*, no. 2540536, 2025.

[42] A. W. Mushtaha, W. S. Alaloul, A. O. Baarimah, M. A. Musarat, K. M. Alzubi, and A. M. Khan, "A decision-making framework for prioritizing reconstruction projects in post-disaster recovery," *Results Eng.*, vol. 25, no. 103693, p. 103693, 2025.

[43] M. C. Okika, A. Vermeulen, and J. H. C. Pretorius, "A systematic approach to identify and manage supply chain risks in construction projects," *J. Financ. Manag. Prop. Constr.*, vol. 30, no. 1, pp. 42–66, 2025.

[44] M. Ishiwatari, "Disaster risk reduction," in *Handbook of Climate Change Mitigation and Adaptation*, Cham: Springer Nature Switzerland, 2025, pp. 3679–3705.

[45] M. Yazdi, S. Adumene, D. Tamunodukobipi, A. Mamudu, and E. Goleiji, "Virtual safety engineer: From hazard identification to risk control in the age of AI," in *Studies in Systems, Decision and Control*, Cham: Springer Nature Switzerland, 2025, pp. 91–110.

[46] S. S. Infant, S. Vickram, A. Saravanan, C. M. Mathan Muthu, and D. Yuarajan, "Explainable artificial intelligence for sustainable urban water systems engineering," *Results Eng.*, vol. 25, no. 104349, p. 104349, 2025.

[47] Y. Teng, Y. Bao, Y. Wang, S. Liu, Z. Li, and R. L. K. Tiong, "Recognizing and reconciling dynamic stakeholder conflicts for sustainability in old residential community renovation project strategies," *Environ. Impact Assess. Rev.*, vol. 110, no. 107693, p. 107693, 2025.

[48] S. Hwang and M. Choi, "Integrative building safety evaluation to mitigate disaster risks: a case study on public-use buildings in Seoul," *J. Asian Archit. Build. Eng.*, pp. 1–15, 2024.

[49] Q. Wang and Y. Liu, "Blockchain empowered dynamic access control for secure data sharing in collaborative emergency management," *Inf. Process. Manag.*, vol. 62, no. 3, p. 103960, 2025.

[50] M. Krichen, M. S. Abdalzaher, M. Elwekeil, and M. M. Fouda, "Managing natural disasters: An analysis of technological advancements, opportunities, and challenges," *Internet of Things and Cyber-Physical Systems*, vol. 4, pp. 99–109, 2024.